ENHANCEMENT OF EFFICIENCY OF SPD PROCESS BY APPLICATION OF NEW GEOMETRY OF ECAP TOOL

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Abstract
At present technologies of production of ultra-fine grained (UFG) metallic materials and subsequently of semis are being used in broader extent both in pilot plants and in industrial practice. Amount of investments necessary for realisation of industrial equipment and afterwards for industrial production is from this viewpoint a critical factor. Research and development works are now focused primarily on enhancement of efficiency of SPD process, which is the core of all these manufacturing technologies. The paper presents comparison of classical geometry of the ECAP tool with the newly designed geometry of the output channel of the ECAP tool (helix). This geometry enables substantial enhancement of efficiency of SPD process. The process was applied to the alloy AlMn1Cu. Necessary refinement of grain was achieved with smaller number of passes.

Keywords: severe plastic deformation, hardness test, TEM, aluminium alloys

1 Introduction

Use of severe plastic deformation (SPD) is highly efficient method leading to grain refinement to the medium grain size, which cannot be achieved by common conventional forming processes. This method is object of basic and applied research. Newly developed technologies use extreme plastic deformations for creation of (UFG) and NC structure. The research is focused primarily on production of materials from non-ferrous metals and their alloys (based on Al, Mg, Cu), since they are characterised by very good mechanical properties with preservation of good formability, and last but not least their specific mass is lower in comparison with normally accessible steel materials. SPD process for production of UFG material based on Mg, Al, Ti finds its application namely at small-lot production, where the stress is not put on large volumes of produced materials, but rather on specific mechanical properties, and where high price of produced materials is accepted by market environment [1-8].

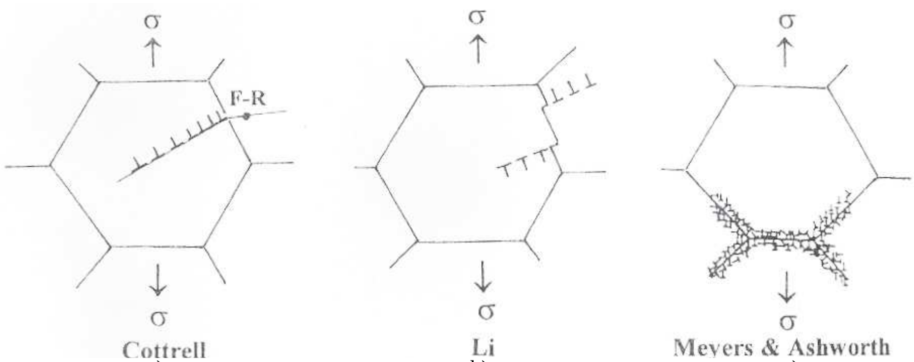
1.1 Principle of enhancement of material properties

Various approaches, and sometimes very sophisticated methods for influencing the structure, are used in order to achieve high strength at satisfactory formability. Research of the core of strength of mostly metallic materials resulted in determination of several mechanisms of strengthening. Grain refinement leads not only to an increase in strength, but also to degradation of plastic properties of materials. Here below are mentioned already known mechanisms aimed at strengthening of structure with focus on mechanisms, which can be observed at development of structure after shear deformation during the equal channel angular pressing (ECAP) process [2, 9, 10].

It is a well known fact that material strength and hardness increases with decreasing grain size in their structure (surface of grain boundaries increases). In the fifties of the last century the authors N. J. Petch and E. O. Hall formulated independently on each other the nowadays well-known Hall-Petch relation of dependence of strength properties of poly-crystalline materials on grain size in the form

$$\sigma_y = \sigma_0 + k.d^{-1/2} \tag{1}$$

Verification of this relation was oriented on determination of limits of its validity. This consisted above all of investigation of the mechanisms, which control the relation in the area of UFG and NC of (nano) structure, the pre-requisite of which is an increase of strength with preservation or only very limited reduction of materials formability [14].



a) b) c)

Fig.1 Three mechanisms describing Hall-Petch relation

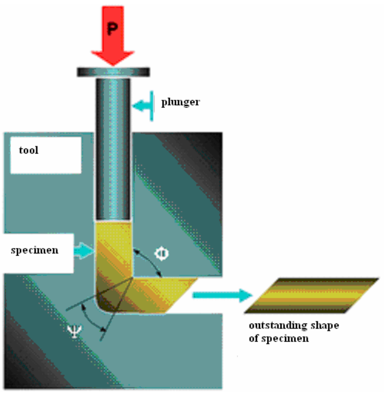
The relation was defined by several mechanisms, three most important of which are mentioned below :

a) accumulation of dislocations before the grain boundary, which at certain stress activate the Frank-Read source in adjoining grain and deformation propagates through the grain and then through the whole material (Cottrell)
b) generation of dislocations at protuberances of grain boundaries, formed at deformation (Li)
c) generation of dislocations, which form at grain boundaries a hardening layer (Myers and Ashworth)

2 Materials and Experimental Research

2.1 Technology ECAP

Technology ECAP, i.e. equal channel angular pressing, uses shear deformation for creation of an UFG structure. The objective of this method consists in creation of severe plastic deformation in material with unchanged cross-section of the specimen. Thanks to the fact that the specimen does not change its cross-section, it is possible to use an accumulation of mechanisms of deformation strengthening after individual passes through the tool [1]. Achievement of severe plastic deformation is possible only by repeated extrusion of specimens through the tool. Extrusion is realised by passage of the specimens through the tool, in which two channels intersect and which form an angle usually of 90° (see **Fig. 2**), this angle can be changed. Shearing stress with deformation intensity after one passage that is usually equal to 1 occurs right during the passage of the specimen through the area, in which the channels intersect. This value depends on inner and exterior angle of the tool channel [2, 15] - see the relation 2.



$$\varepsilon_{VM} = \frac{2 \cdot n}{\sqrt{3}} \cdot \left[\cot\left(\frac{\phi}{2} + \frac{\psi}{2} \right) + \psi \cdot \frac{1}{\sin\left(\frac{\phi}{2} + \frac{\psi}{2} \right)} \right] \quad (2)$$

Fig.2 Classical geometry of the ECAP tool

It follows from the above relation that higher degree of deformation after one pass can be achieved by modification of the channel geometry. An optimum geometry of the channel was investigated in numerous works; it appears from the results that optimum angles are Φ = 90° and Ψ = 20°. "N" in the relation takes into account the number of passes through the tool, which comprises an accumulation of deformation intensity after individual passes. Another parameter, which influences the resulting structure and therefore mechanical properties, is an appropriate choice of the route of deformation.

2.2 Design of new geometry of the ECAP tool

The tool differs from the basic concept of geometry of the ECAP tool by created helical part in horizontal area of the channel with an angle of lead γ = 10° [3, 4]. The basic aim of use of helix consisted in simulation of back pressure and thus in increase of extrusion force. The tool was made of tool steel made by the company Böhler-Uddeholm under commercial name HOTVAR®. This tool steel is characterised by high strength properties at higher temperatures. It can be quenched and annealed up to 58 HRC, which gives a very good pre-requisite for hot forming. It is therefore possible to verify an influence of temperature at extrusion by the ECAP process. Use of channel connection at the angle of 90° appears to be highly efficient from the viewpoint of achievement of the required degree of deformation [11]. The basic channel geometry is given by the angles Φ = 90° (channel inner angle) and Ψ = 9° 30´. Channel exterior angle Ψ is given by the chosen radii R1 = 0.2 mm and R2 = 2.5 mm [12, 13]. Diagram of the used ECAP tool is shown in **Fig.3**.

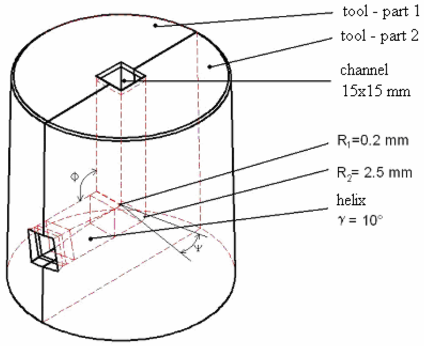


Fig.3 Diagram of new geometry of the ECAP tool

2.3 Selection of material for experiments

The alloy AlMn1Cu is a commercially produced aluminium alloy, which finds its applications in machine-building and food industries. The alloy was supplied by the company Al INVEST Bridlicna, a. s., Czech Republic. The company supplied in a standard manner the material in the form of hot rolled strips with slight reduction up to 10% after pass through the rolls. The as rolled strip had temperature of approx. 370°C and 11 ton strip cools down to an environmental temperature for two days. Test specimens for experimental purposes, which were formed by 5 passes and had dimensions 15x15x60 mm, were cut in direction of rolling [4]. After casting and rolling the yield strength of material has achieved the value of 140 MPa. Chemical composition and basic mechanical properties of the alloy AlMn1Cu are summarised in the **Tables 1** and **2**.

Table 1 Chemical composition of AlMn1Cu

Mn	Fe	Si	Cu	Other	Al
1.1%	0.45%	0.55%	0.15%	up to 0.05%	rest

Table 2 Basic mechanical and physical properties

Rm (MPa)	Re (MPa)	E (GPa)	υ	Specific mass $\rho_{20°}$ (kg.m-3)	Crystal lattice
154	140	72	0.33	2700	csc

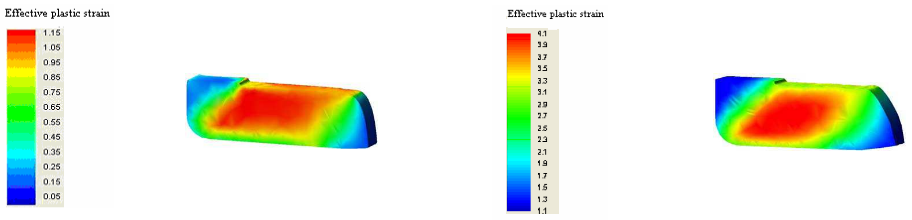
Fig.4 Experimental working site with hydraulic press of the type DP 1600 kN

The experiments were realised at the working site of the Department of Mechanical Technologies, Faculty of Mechanical Engineering, Technical University of Mining and Metallurgy in Ostrava (VŠB-TU Ostrava). Hydraulic press DP 1600 kN with servo-operated valve enabling gradual control from control panel coupled with temperature regulator was used for extrusion (see **Fig. 4**) [11, 12].
Materials were reheated up to the temperature of 1100°C in induction furnace.

3 Results and discussion

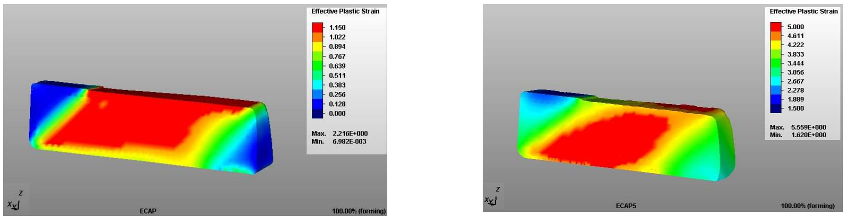
3.1 Mathematical simulation of ECAP technology with classical and new tool geometry

Program SimufactForming was used for mathematical simulation. Achieved results are stated in **Fig.5** and, **Fig.6** and in the **Table 3**.



a) b)

Fig.5 Achieved magnitude of effective plastic strain a) at the 1st pass, b) at the 5th pass through the ECAP tool



a) b)

Fig.6 Achieved magnitude of plastic strain a) at the 1st pass, b) at the 5th pass through the ECAP tool (new geometry)

Results of mathematical simulation have confirmed unequivocally a contribution of the new geometry of the ECAP tool to the enhancement of efficiency of SPD process [4].

Table 3 Achieved max. magnitude of effective plastic strain in classical and new geometry of the ECAP tool

Number of passes	1	3	5
$\varepsilon_{clas.}$ (classical tool)	1.0-1.1	3.1	4.6
$\varepsilon_{new-geom}$ (new geometry of tool)	1.9-2.0	4.2	5.6

3.2 Measurement of hardness

Hardness in the alloy AlMn1Cu was measured on the surface and in the central part of the specimen. Indents on the surface were made in both longitudinal and transversal direction. Measurement of hardness in the central part was made in longitudinal direction, which is also the direction of rolling [4, 12]. The biggest increase in hardness was achieved already after the 1st pass through the tool 54.5 HV, after that an increase of hardness was decreasing with an increasing number of passes. At the 5th pass a hardness of 70.2 HV was measured on the surface, which represents an increase in hardness by 100 % in comparison to the initial state (initial state – 35 HV, (see **Fig. 7**).

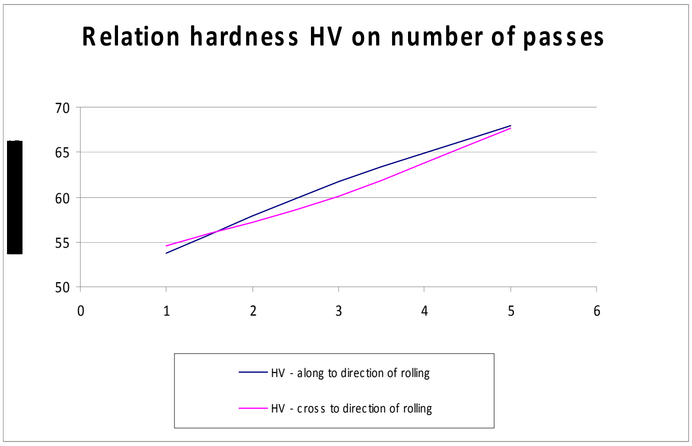
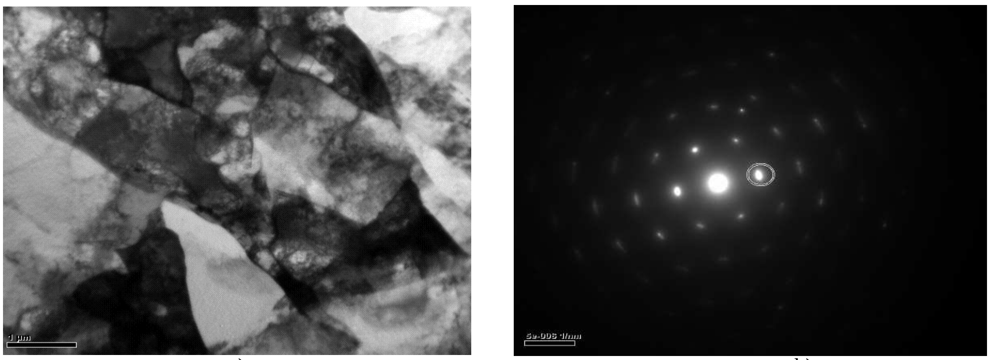


Fig.7 Achieved magnitude of hardness after the 1st to 5th pass through the ECAP tool with new geometry

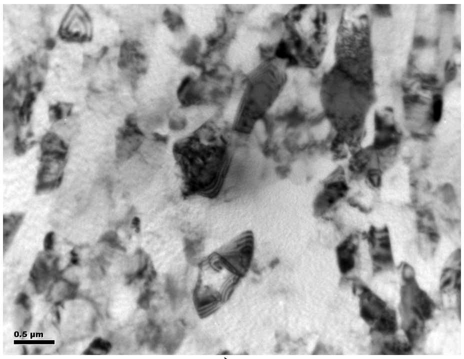
The measured values describe very well the fact that hardness in the central part does not differ significantly from the hardness achieved on the surface of specimens for the same number of passes through the tool. This finding corresponds with initial assumptions and it has also confirmed and enhancement of efficiency of SPD process.

3.3 Metallographic analysis

Analysis of structure of the alloy AlMn1Cu was made on TEM and with use of SAED. Analysis concerned the initial state and the state after the 5th pass through the ECAP tool containing the helix. Discs with thickness of 3 mm were taken from the specimen after the 5th pass. These disks were then ground and polished to the final thickness of 0.13 - 0.15 mm. In this manner the specimens were prepared. Results of metallographic analysis (TEM and SAED) are shown in **Fig. 8**.



a) b)



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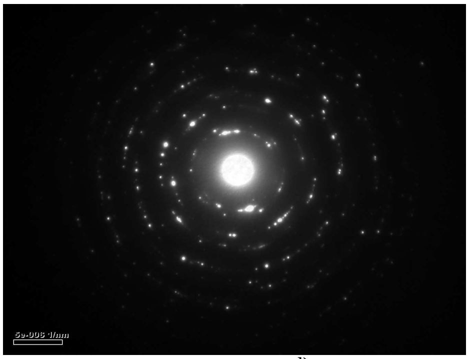

d)

Fig.8 Metallographic analysis – of initial state a) TEM, b) SAED, state after the 5th pass, new tool geometry c) TEM, d) SAED

Initial grain size achieved the values of the order of 150 – 200 μm. Substantial grain refinement was achieved - from 250 to 400 nm (average grain size) [4]. High degree of grain refinement was achieved.

4 Conclusions

Mathematical simulation and realised experiments with use of the ECAP technology have confirmed unequivocally the rightness of the new concept of the ECAP tool geometry aimed at refinement of grain in the alloy AlMn1Cu. It brought a substantial increase in efficiency of SPD process, which is the core of this technology. Measurements of hardness proved that an increase in hardness of 100% had been achieved after the 5th pass through the ECAP tool in comparison to the initial state. High increase of hardness (up to 50 %) had been achieved already after the 1st pass, which is an entirely new finding, confirming high efficiency of the process. Analyses of structure on TEM and SAED have confirmed high grain refinement achieved in the 5th pass. These results bring new findings in the given area of scientific research.

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